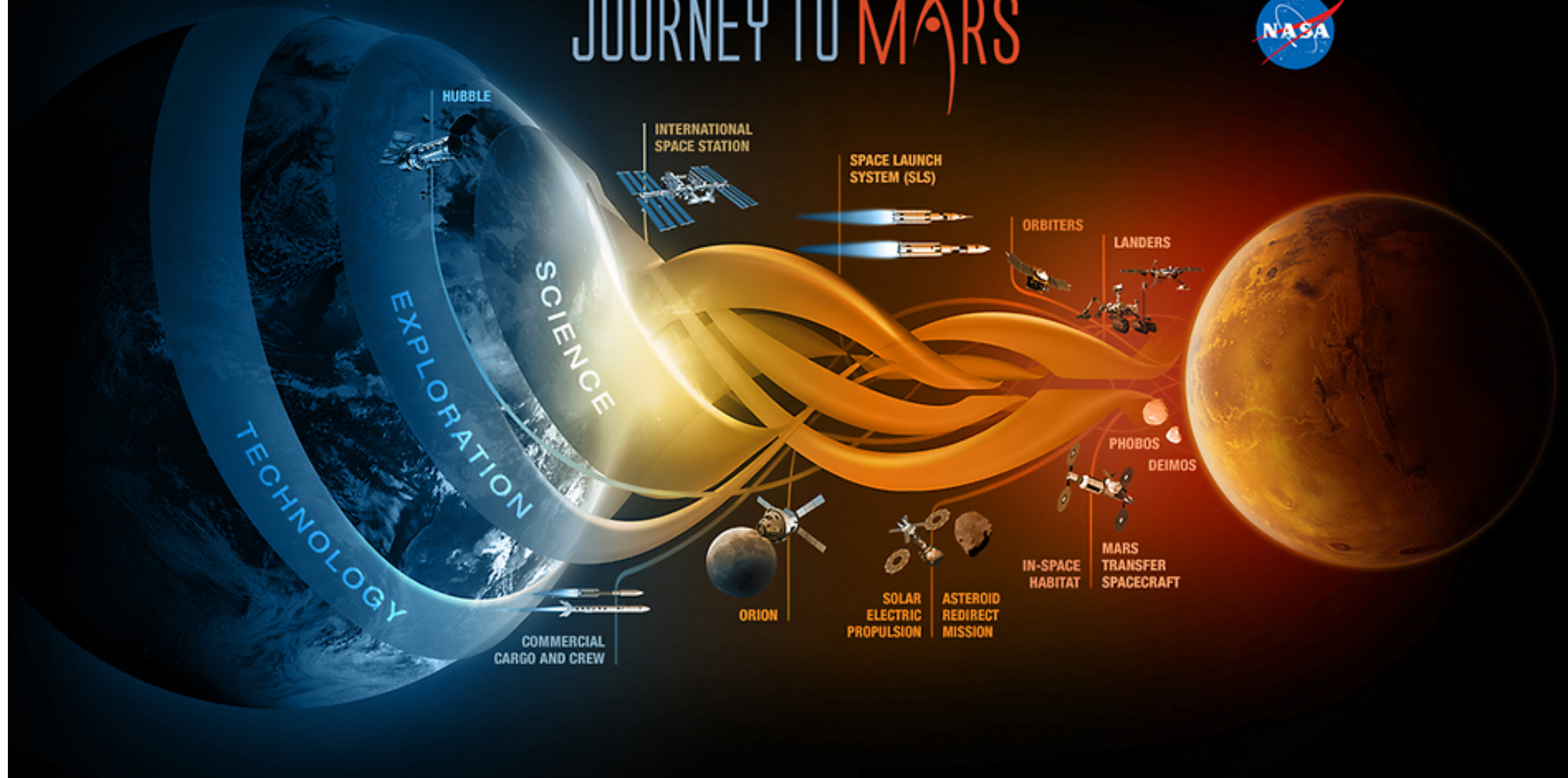


Challenges of In-space Additive Manufacturing

Michael Waid

NASA Johnson Space Center

JOURNEY TO MARS



Case for In-space Manufacturing

- Logistics Supportability
 - Limited mass and volume allocation
 - Limited or no re-supply capability
 - Mars Tranist missions will have no re-supply
 - Mars and Lunar surface missions have limited re-supply capability and cargo vehicle arrival durations are in extended time periods.
- Failure Tolerance
 - Sparing for diverse mechanisms and tools
 - Structural damage at different locations and structural configurations/geometry
 - Designing and developing doublers for all possible damages and locations is not feasible.
 - Custom structural doubler manufacturing on the ground and re-supplying to the spacecraft is not an option.

Why Additive Manufacturing (AM)?

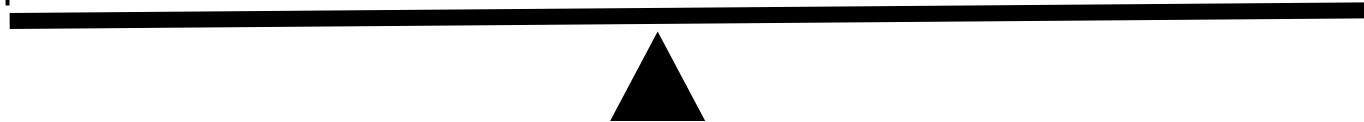
- Minimized Material Usage
- Reduced Material Removal
- Generic Feedstock
- Complex Geometries
- Reduced Part Count

System trade required for cost-benefit

Trade Flexibility, Mass, Volume, Power, Crew time, data, reliability, etc.

Fly repair kits and spares
for as many situations as
possible

Fly flexible additive
mfg/repair system +
generic feedstock








Historical - In-space Manufacturing (Metallic)

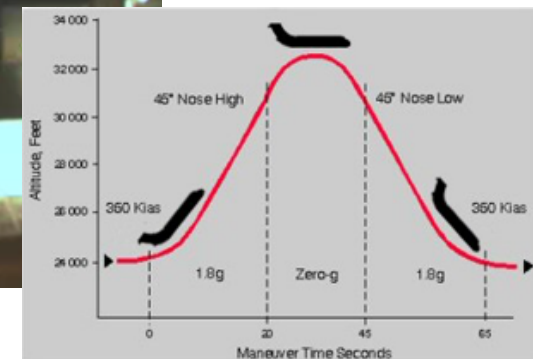
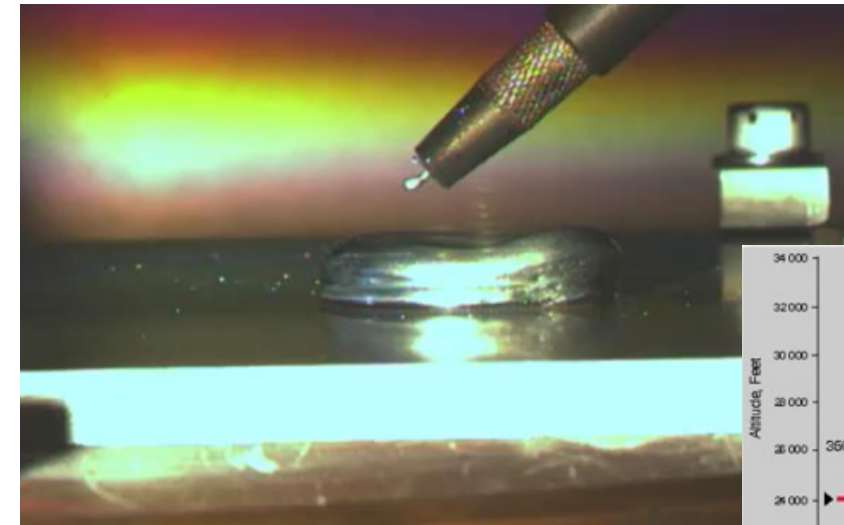
In-space Welding

- Long History of Space Welding Development for Repair and Joining
- Safety concerns for space shuttle experiment due to manual operation by crew member in fabric space suit
- Prior to capable Extravehicular Robotics (EVR) and additive manufacturing

- Electron Beam Freeform Fabrication (EBF³) developed by NASA LaRC
- Electron Beam, Wire Feeder, and positioning system deposit near-net-shape material in vacuum
- Demonstrated that surface tension enables deposition of melt pool in microgravity

Year	Activity	Country	Process	Vehicle	Images	Outcome
1969	Vulcan, Self-contained experiment	Russia	EB, Arc	Soyuz 6		First demonstration of on-orbit welding.
1973	M551 Materials Melting, Self-contained experiment	US/MSFC	EB	Skylab 1		Demonstrated metallurgy of 2219-T87 welds in microgravity.
1984	First Manual Electron On-orbit Manual Weld	Russia/Ukraine	EB	Salyut 7		Demonstrated concept and challenges of maintaining control during welding in a space suit.
1989	On-orbit Electron Beam Welding Experiment Definition	US (MSFC/Martin Marietta)	EB	Ground Demo only		Demonstrated on-orbit repair concept, weld schedule, and 2219-T87 metallurgy utilizing beam deflection.
1990s	International Space Welding Experiment	US (MSFC)/Ukraine (Paton Weld Institute)	EB	Space Shuttle (Not Flown)		Demonstrated safety challenges associated with manual EVA welding.

EBF³ C9 Reduced Gravity Aircraft Testing



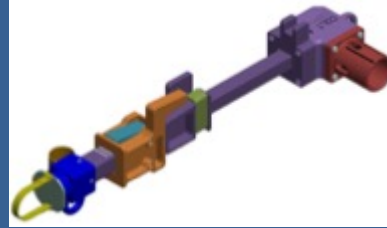
K. Taminger, Langley Research Center

Historical – Part Additive Manufacturing and Certification Pathfinder (2011)

Receptacle - Coarse Alignment Guide

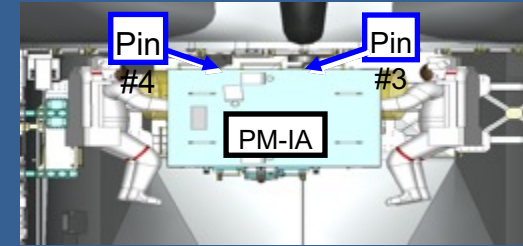
- Receptacle used on last shuttle flight
- Additive part fabricated concurrent to flight part (as flight, not flown)
- Electron Beam Freeform Fabrication
- Point certification to pathfind certification process

Application



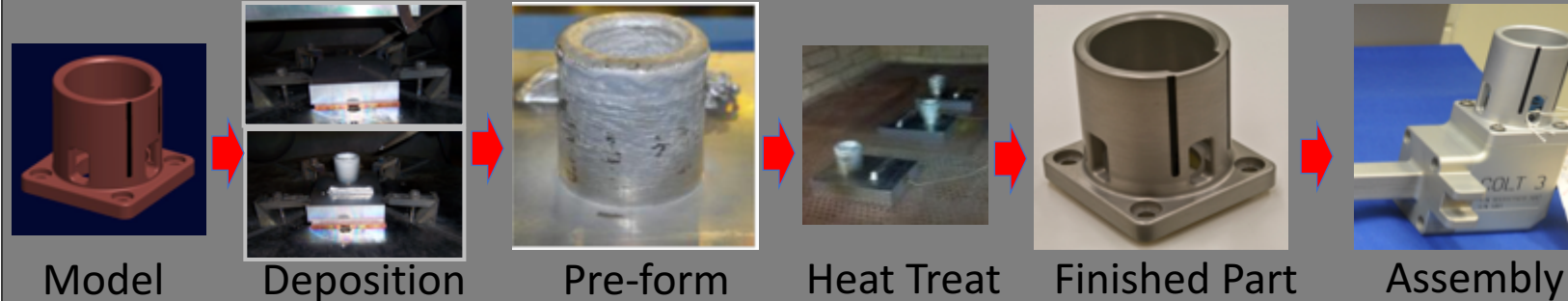
Receptacle

COLT EVA Contingency Tool

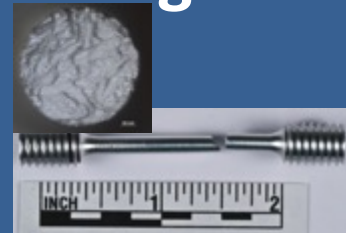


STS-135 Pump Module Return

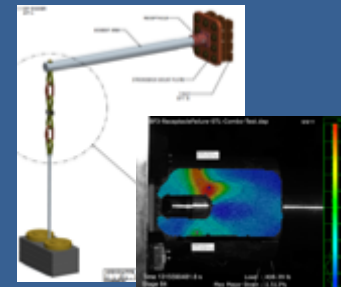
Fabrication



Testing



Coupon Testing



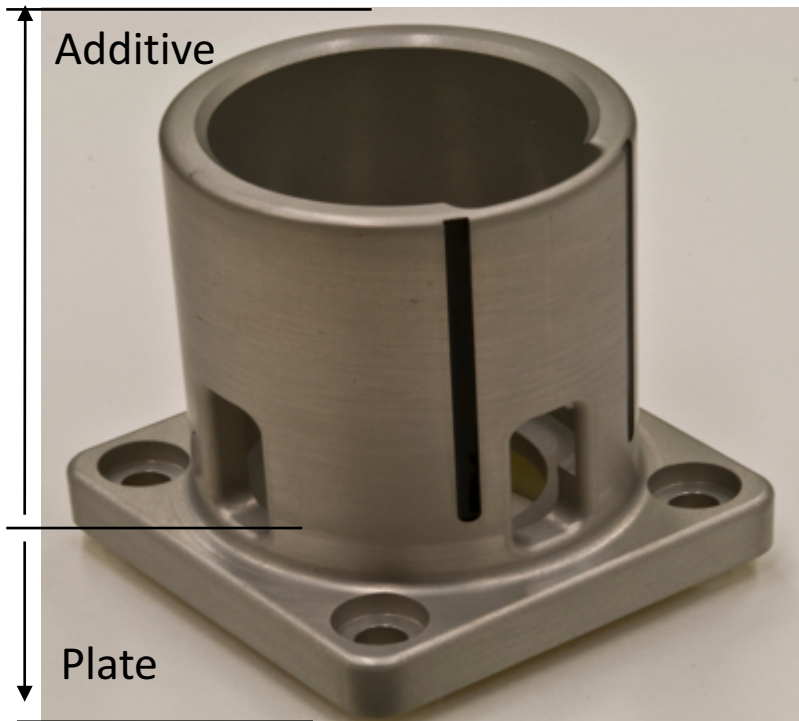
Part Testing



Inspection



Metallography



Challenges – Additive Manufacturing (AM)

- Structural Certification Approach
- Process-dependent Material Allowables (process control)
 - Properties dependent on process and location in part
 - Many process variables
- Defects
 - Porosity
 - Line defects
- Tolerances, Finish Machining, and Residual Stresses
- Non-destructive Evaluation
 - Rough surfaces
 - Complex Geometries
- Design for Manufacturability

Application - Exploration AM Sparing Concept

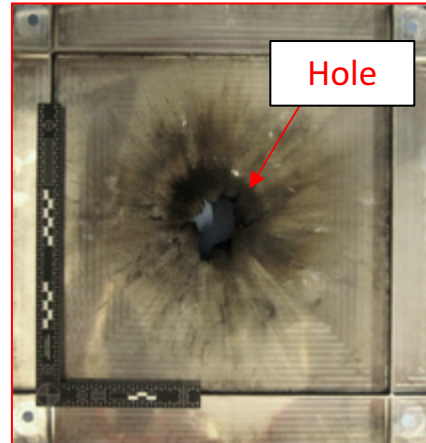
- System design incorporates component-level sparing
- Original design accommodates use of AM for sparing
 - Original parts are fabricated with AM or
 - AM part/material listed as acceptable alternate
- Before mission, certification of AM part on the ground
- On-demand AM of parts as needed
- On-orbit process control and acceptance testing for verification

Application - Habitable Module Pressure Wall Repair

Scenario: Micrometeoroid Orbital Debris Penetrates Module Pressure Wall. Structural doubler required.



ISS Module

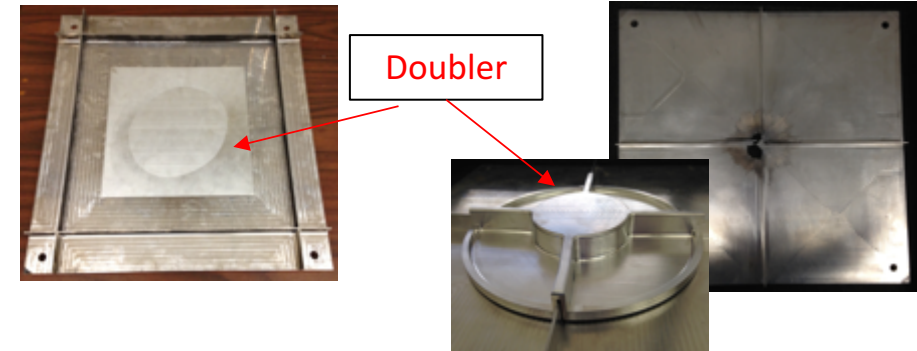


Damage

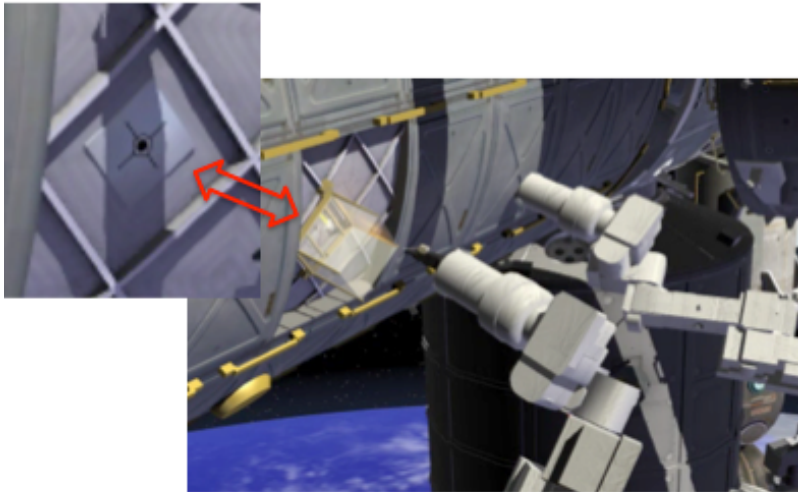
Repair Options:

- 1) Custom doubler machined and welded over damage
- 2) Doubler additively deposited directly over damage

Machined Doublers over damage

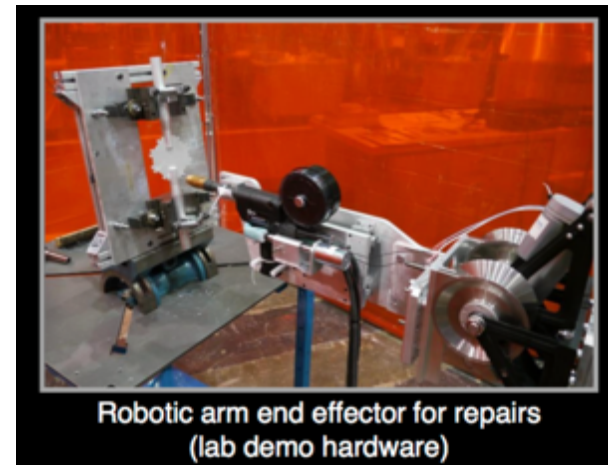


Doubler Robotic Welding or Additive Deposition Concept



Note: SPDM shown does not have resolution for additive, but other EVR could be used.

Robotic Additive Deposition Repair Testing



Robotic arm end effector for repairs (lab demo hardware)



K. Taminger, Langley Research Center

Development Recommendations

- Develop AM process control and 'allowable' approach
- Perform additional AM part and repair demonstrations
- International Space Station AM experiment to further study metal deposition and develop material properties in microgravity/space environment
- Perform system trade studies to evaluate cost-benefit
- Develop system concept for exploration manufacturing/repair system
 - Autonomous Operation and Data Architecture
 - Space robotics
 - System Packaging
 - Reduced Mass/Volume/Power
 - Integrated Finish Machining
 - Integrated Dimensional and Non-Destructive Evaluation
 - Fixtures and Assembly
 - Quality and Inventory Management
 - Crew Safety and Health